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Cylinder Strength versus Cube Strength

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Outline

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4. Discussion
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1. Background

Design of public works civil engineering structures mainly makes reference to British Standards, such as:

- BS 5400: Bridges
- BS 8004: Foundations
- BS 8007: Water retaining structures
- BS 8110: Structural use of concrete

The above standards were superseded by Eurocodes:

BS EN 1990:2002+A1:2005, BS EN 1991-1-7:2006,
BS EN 1992-1-1:2004, BS EN 1992-3:2006,
BS EN 1997-1:2004, etc.

1. Background

DEVB planned to migrate to Eurocodes for the design of public works civil engineering structures by 2015.

In BS EN 1992-1-1:2004, Eurocode 2: Design of concrete structures, characteristic cylinder strength (f_{ck}) is used in most of the design formulae.

In BS EN 206-1:2000:

The characteristic strength at 28 days of 150 mm diameter by 300 mm cylinders or the characteristic strength at 28 days of 150 mm cubes are used for classification.

BS EN 206-1, Table 7 gives the following correlation:

Compressive strength class	Characteristic cylinder strength $f_{ck,cyl}$ N/mm^2	Characteristic cube strength $f_{ck,cube}$ N/mm^2	Cylinder/ cube strength ratio
C8/10	8	10	0.80
C12/15	12	15	0.80
C16/20	16	20	0.80
C20/25	20	25	0.80
C25/30	25	30	0.83
C30/37	30	37	0.81
C35/45	35	45	0.78
C40/50	40	50	0.80
C45/55	45	55	0.82
C50/60	50	60	0.83
C55/67	55	67	0.82
C60/75	60	75	0.80
C70/85	70	85	0.82
C80/95	80	95	0.84
C90/105	90	105	0.86
C100/115	100	115	0.87

In HK, 100 mm cubes are commonly used for determining the compressive strength of concrete as the maximum aggregate size used in concrete mixes is normally 20 mm.

According to GS 2006, Cl.16.59(6):

The size of the test cube shall be 100 mm for concrete with the maximum aggregate size not exceeding 20 mm and shall be 150 mm with the maximum aggregate size exceeding 20 mm.

In order to investigate if the Eurocode relationship between cylinder strength and cube strength also holds for local concrete, DEVB proposed to carry out a study in late 2012.

The aim is to study the correlation between 150 mm dia. by 300 mm cylinder strength and 100 mm cube strength for local concrete.

2. Methodology

1. A study brief was written by WSD in consultation with CEDD and Prof. Kwan of HKU. Originally, it was intended to produce 50 sets of cylinder and cube samples for each grades of concrete ranging from 10 MPa to 95 MPa.

2. After discussion with DEVB, Prof. Kwan of HKU volunteered to arrange the casting of samples and carry out the testing for the study.

2. Methodology

With a view to shorten the study period and reduce the number of samples, Prof. Kwan modified the sampling requirements as following:

- Three sets of cylinder and cube samples from each of the grades of concrete ranging from 10 MPa to 95 MPa.
- 100 mm Cube: 3 samples, two specimens for each sample.
- 150 dia. x 300 mm cylinder: 3 samples, two specimens for each sample.

Testing

Between late 2012 and Jan. 2013, a total of 126 cubes and 126 cylinders were cast by concrete suppliers and two public works contracts.

The PWCL was subsequently requested to take over the testing of concrete samples due to some difficulties in HKU in the testing of cylinders.

By Feb. 2013, PWCL completed all the tests in accordance with CS1.

3. Analysis of test results

(1) It is found that the actual cube test results ranged from about 10 MPa to 130 MPa. They were grouped into 12 strength bands ranging from 10-20 MPa to 120-130 MPa.

(2) According to GS2006:

1. The test result of a sample shall be the average compressive strengths of the two specimens tested at 28 days.
2. If the difference between the compressive strengths of two test cubes made from one sample of designed mix concrete exceeds 15% of the test result, the test result for that sample shall not be used to calculate the standard deviation.

According to BS EN 206-1:2000

The test result should be discarded in case the range of the two compressive strengths is more than 15% of the average of the two compressive strengths.

3. Analysis of test results

Test results for study on cylinder vs cube strength

Actual Cube Strength Range	Test results, MPa											
	Cylinder						Cube					
	1	2	Average	Mean	S.D.	$f_{ck,cyl}$	1	2	Average	Mean	S.D.	$f_{ck,cube}$
10-20MPa	9.3	9.8	9.6				12.3	12.9	12.6			
	9.0	9.7	9.4	9.4	0.4	8.8	11.8	11.9	11.9	12.3	0.4	11.6
	9.0	9.7	9.4				12.2	12.7	12.5			
20-30MPa	23.6	21.4	22.5				27.1	26.7	26.9			
	21.6	22.7	22.2	22.3	0.8	20.9	26.9	27.5	27.2	27.1	0.6	26.1
	22.5	21.9	22.2				27.9	26.3	27.1			
30-40MPa	22.0	25.6	23.8				31.4	29.4	30.4			
	31.2	30.3	30.8	29.1	2.4	25.2	32.0	34.5	33.3	30.8	2.3	26.9
	28.9	25.8	27.4				29.1	28.2	28.7			
	26.5	24.9	25.7				30.9	30.7	30.8			
	33.3	31.1	32.2	27.6	3.7	21.6	36.7	35.5	36.1	31.6	3.8	25.5
	25.1	24.9	25.0				29.0	27.0	28.0			
	20.7	22.4	21.6				31.1	34.2	32.7			
	22.0	19.3	20.7	21.0	1.2	19.1	31.9	31.9	31.9	32.3	1.0	30.6
	21.7	20.1	20.9				32.3	32.3	32.3			
40-50MPa	39.4	40.6	40.0				48.7	48.6	48.7			
	33.9	33.8	33.9	36.2	3.0	31.3	44.9	43.3	44.1	45.0	3.0	40.1
	34.4	35.3	34.9				42.1	42.5	42.3			
50-60MPa	47.1	40.8	44.0				57.6	55.3	56.5			
	48.2	49.5	48.9	47.9	3.8	41.6	55.3	59.6	57.5	57.0	1.6	54.4
	49.6	51.9	50.8				57.4	57.0	57.2			
	37.5	37.6	37.6				50.9	50.1	50.5			
	37.3	37.3	37.3	37.4	0.4	36.7	45.2	56.4	50.8	51.4	3.8	45.3
	36.8	38.1	37.5				53.1	52.9	53.0			
60-70 MPa	48.2	47.7	48.0				65.8	65.6	65.7			
	45.3	46.2	45.8	47.1	1.3	44.9	56.9	57.1	57.0	61.8	4.0	55.2
	48.7	46.4	47.6				63.7	61.4	62.6			
	53.8	54.5	54.2				71.1	66.5	68.8			
	56.8	56.8	56.8	56.3	1.8	53.4	68.1	69.9	69.0	69.4	1.7	66.5
	57.4	58.4	57.9				70.2	70.4	70.3			
	56.0	58.7	57.4				66.0	65.6	65.8			
	56.2	50.7	53.5	54.4	3.2	49.1	64.8	69.4	67.1	66.5	2.0	63.1
	50.9	53.7	52.3				57.9	67.3	62.6			

3. Analysis of test results

Test results for study on cylinder vs cube strength

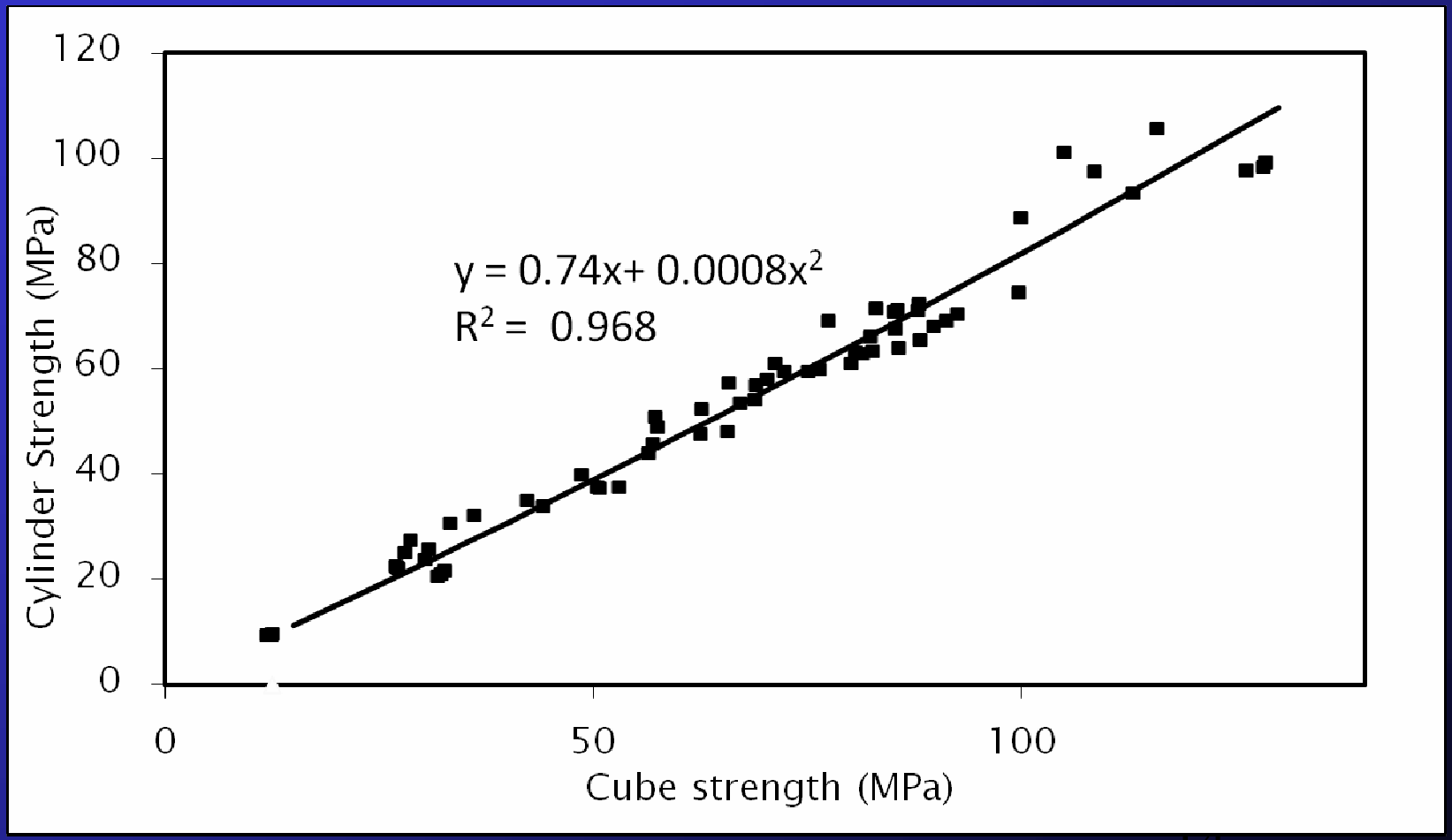
Actual Cube Strength Range	Test results, MPa											
	Cylinder						Cube					
	1	2	Average	Mean	S.D.	$f_{ck,cyl}$	1	2	Average	Mean	S.D.	$f_{ck,cube}$
70-80 MPa	61.2	60.9	61.1				68.4	74.0	71.2			
	70.8	72.3	71.6	67.3	5.0	59.1	82.0	83.9	83.0	77.2	5.7	67.8
	68.2	70.2	69.2				75.4	79.5	77.5			
	59.3	59.8	59.6				74.8	75.4	75.1			
	65.4	66.9	66.2	62.9	3.0	58.0	82.0	82.7	82.4	79.6	3.5	73.8
	62.8	63.0	62.9				80.9	81.8	81.4			
80-90 MPa	60.6	58.1	59.4				71.8	72.8	72.3			
	66.7	69.4	68.1	62.8	4.3	55.7	89.7	89.9	89.8	80.7	7.9	67.8
	60.0	62.0	61.0				81.6	78.6	80.1			
	60.8	58.8	59.8				76.5	76.3	76.4			
	63.6	62.7	63.2	63.5	3.7	57.4	81.0	80.2	80.6	80.8	4.2	73.9
	65.8	69.3	67.6				87.3	83.3	85.3			
	70.0	74.8	72.4				89.7	86.3	88.0			
	64.8	61.7	63.3	66.5	4.9	58.4	82.0	83.3	82.7	85.5	2.7	81.0
	64.3	63.4	63.9				85.1	86.3	85.7			
	71.4	70.3	70.9				81.4	88.7	85.1			
	69.4	73.0	71.2	71.0	1.3	69.0	84.6	86.4	85.5	86.2	2.7	81.6
	71.6	70.4	71.0				87.9	87.9	87.9			
90-100 MPa	73.8	67.1	70.5				91.2	93.8	92.5			
	68.7	62.2	65.5	68.4	3.8	62.1	86.8	89.5	88.2	90.6	2.4	86.7
	68.3	70.0	69.2				92.1	90.3	91.2			
100-110 MPa	73.4	75.4	74.4				95.5	103.9	99.7			
	95.4	99.6	97.5	86.9	10.5	69.6	105.2	111.8	108.5	102.7	6.0	93.0
	88.7	88.6	88.7				103.1	96.8	100.0			
110–120 MPa	93.6	93.2	93.4				113.1	112.8	113.0			
	105.7	105.5	105.6	100.1	5.6	90.9	116.7	114.9	115.8	111.2	5.1	102.9
	100.0	102.4	101.2				105.2	104.6	104.9			
120-130 MPa	94.8	101.9	98.4				130.6	125.7	128.2			
	99.3	99.0	99.2	98.8	2.9	93.9	129.8	127.2	128.5	127.6	2.1	124.2
	105.7	89.8	97.8				126.1	126.4	126.3			

3. Analysis of test results by HKU

HKU carried out an analysis using regression technique based on the average values. The following best fitting curves were obtained:

(i) 150 mm cylinder strength (y) to 100 mm cube strength (x) ratio is given by: **y/x = 0.74 + 0.0008 x** or

(ii) 150 mm cylinder strength (y) to 100 mm cube strength (x) ratio is given by: **y/x = 0.75 + 0.0007 x**



3. Analysis of test results by PWCL

Due to the small number of test specimens within each strength band, PWCL found that the standard deviation within each strength band is sometimes quite large especially at higher strength. A better curve fitting may be achieved if we separate the data into 2 zones, below 80 MPa and above 80 MPa.

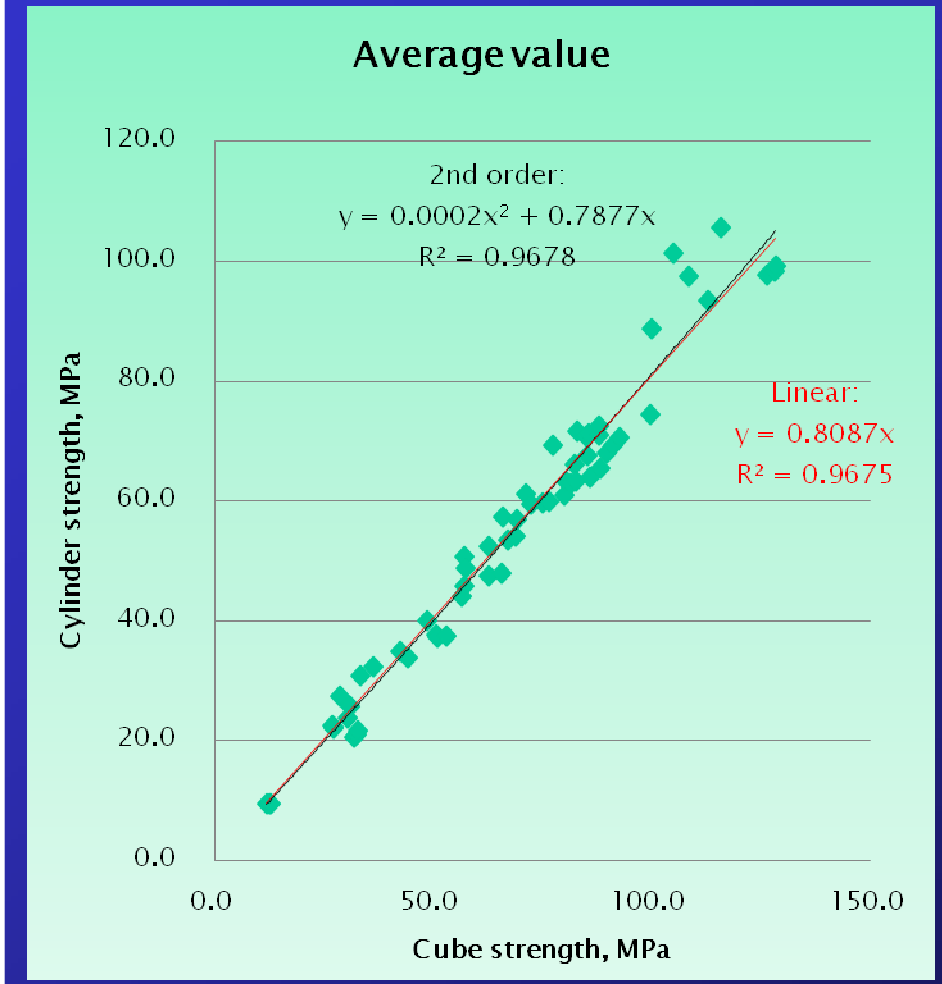
HKU suggests that:

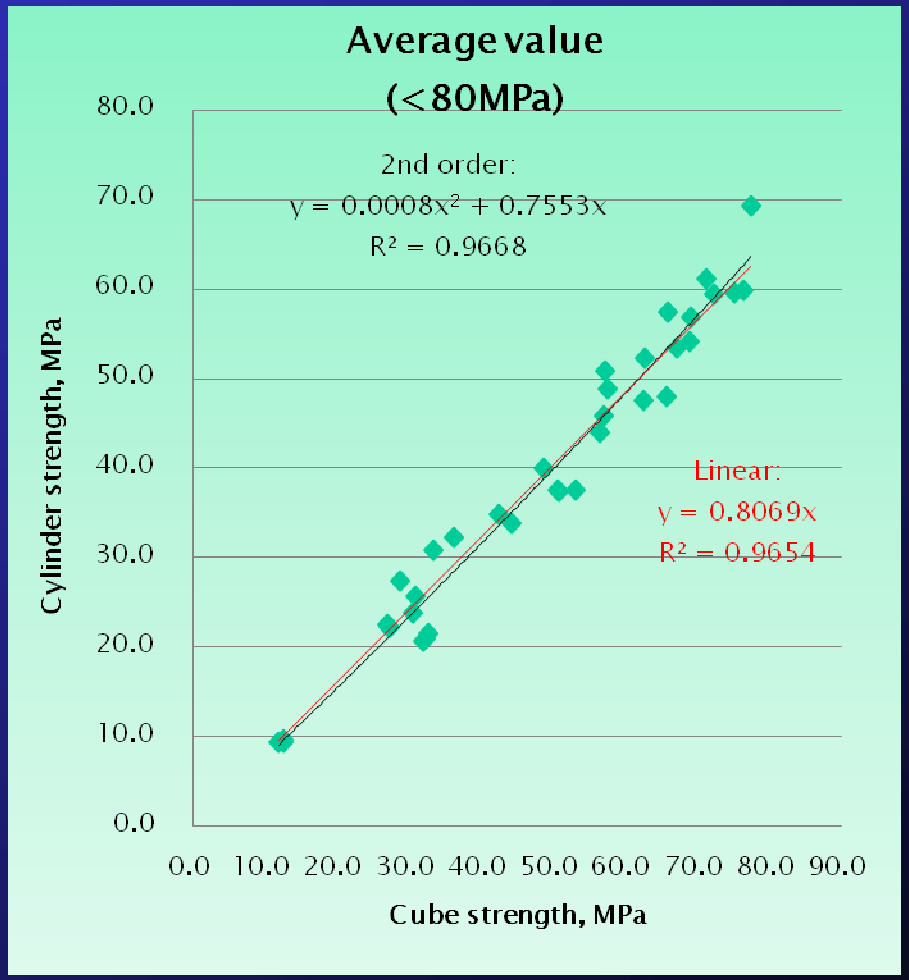
Concrete cube strength up to 80 MPa: a fixed coefficient 0.78

Concrete cube strength higher than 80 MPa: a fixed coefficient 0.80

3. Analysis of test results by PWCL

PWCL obtained similar results based on the average values of two specimens





3. Analysis of test results by PWCL

In Eurocode, the design formulae mainly use characteristic cylinder strength.

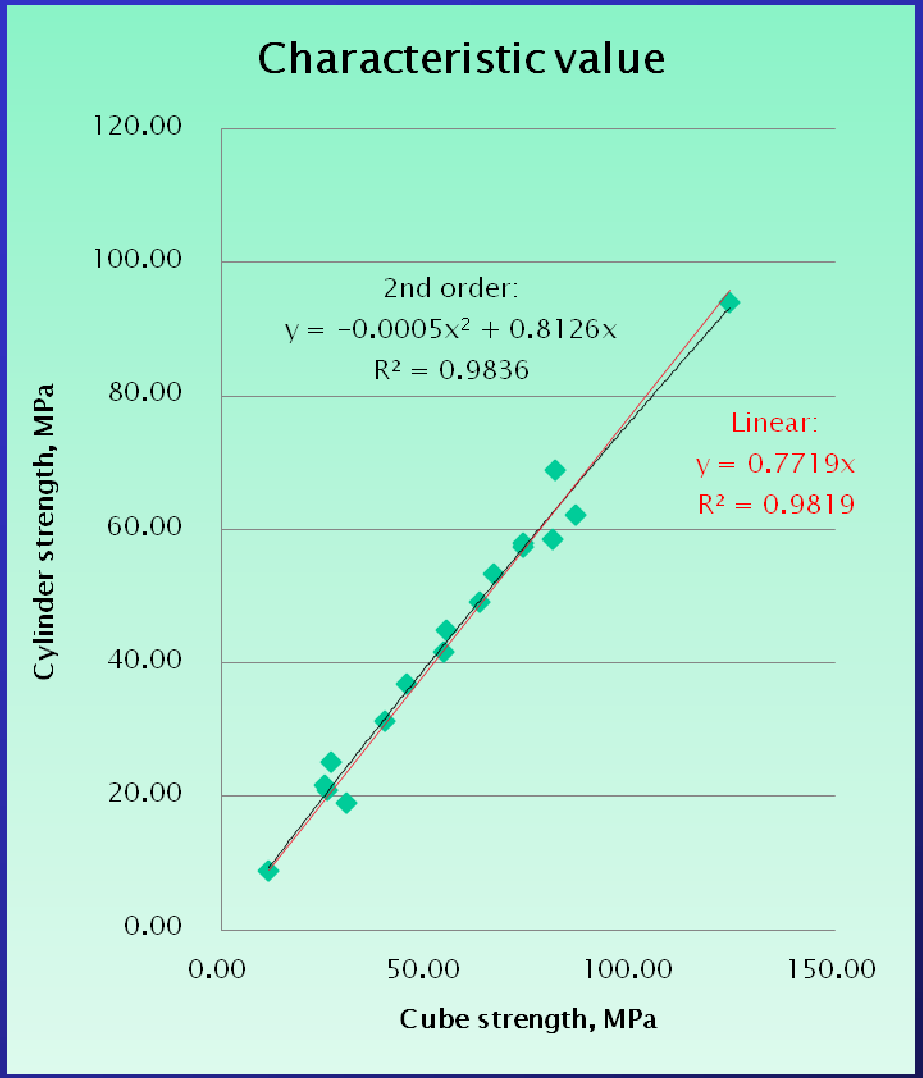
According to Cl.16.05 of GS Guidance Notes and BS EN 206, characteristic strength is the strength that 5% of samples fail to reach.

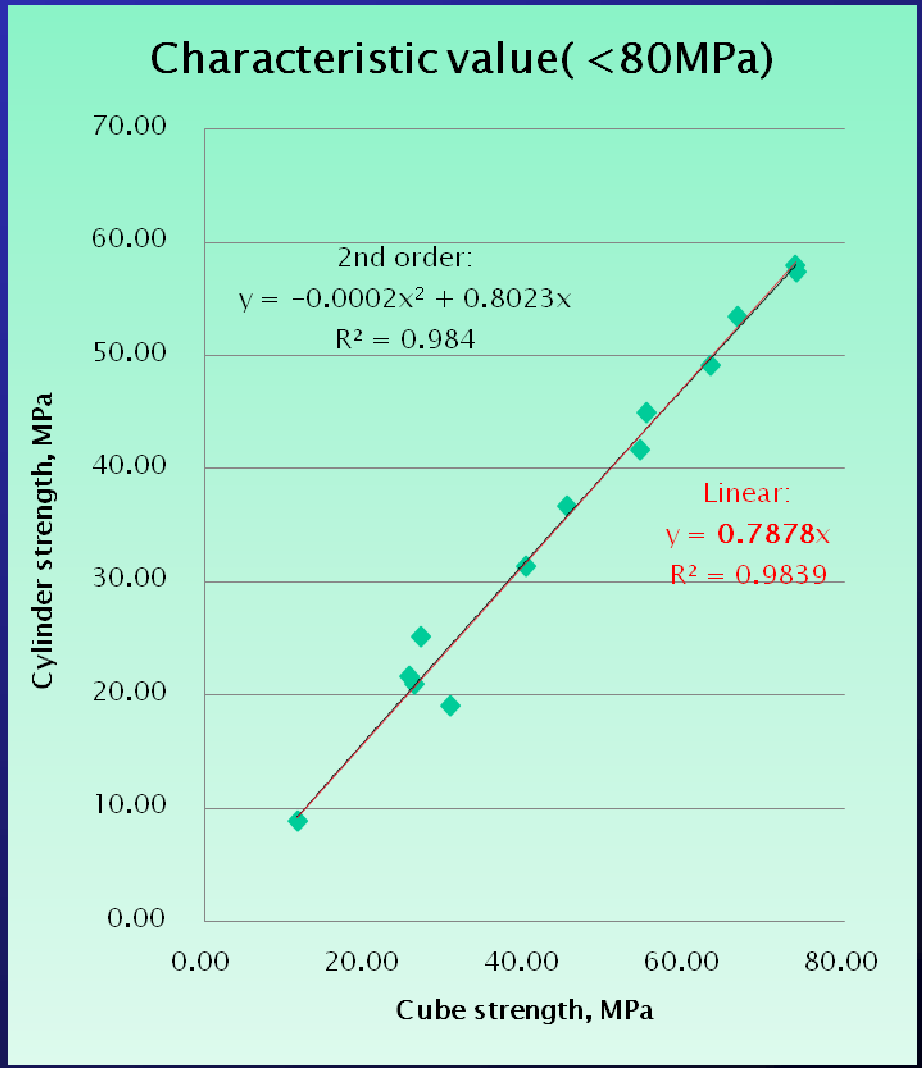
Characteristic strength = Mean strength – 1.64 x standard deviation.

3. Analysis of test results by PWCL

PWCL carried out regression analysis using on the characteristic value of strength grade and found the following relationship.

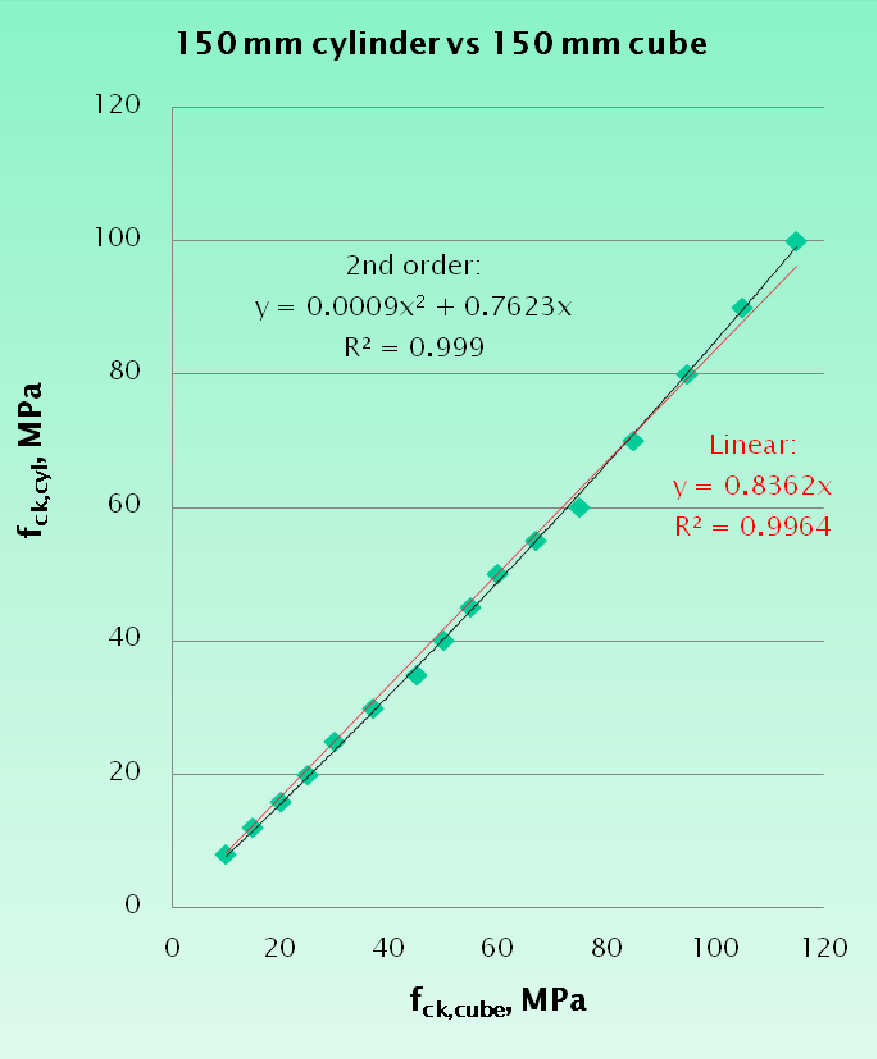
(Test results with S.D. larger than 5 MPa were discarded.)

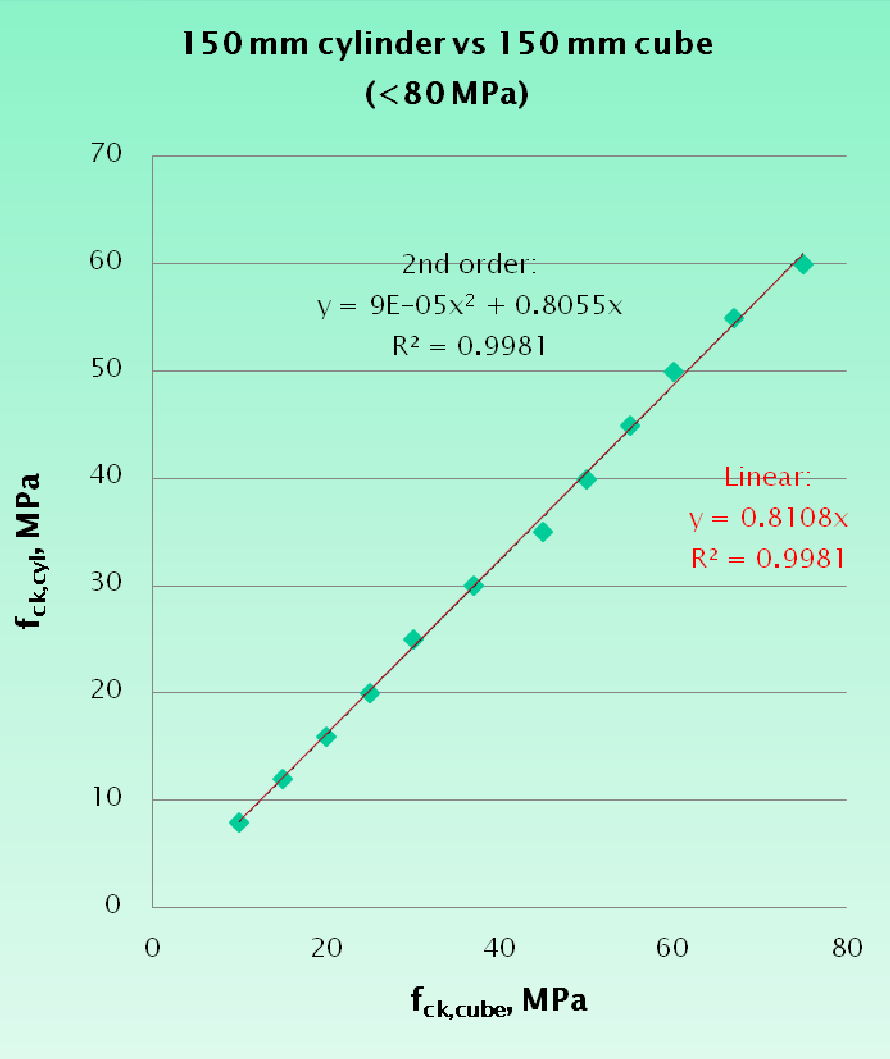




3. Analysis of test results by PWCL

Table 7 of BS EN 206-1





3. Analysis of test results by PWCL

According to Special Project Report SPR 3/96, the 28-day strength of 100 mm cubes is on average about 5% higher than that of the 150 mm cubes.

Convert the 150 mm cube strength (in BS EN 206) into 100 mm cube strength by a factor of 1.05.

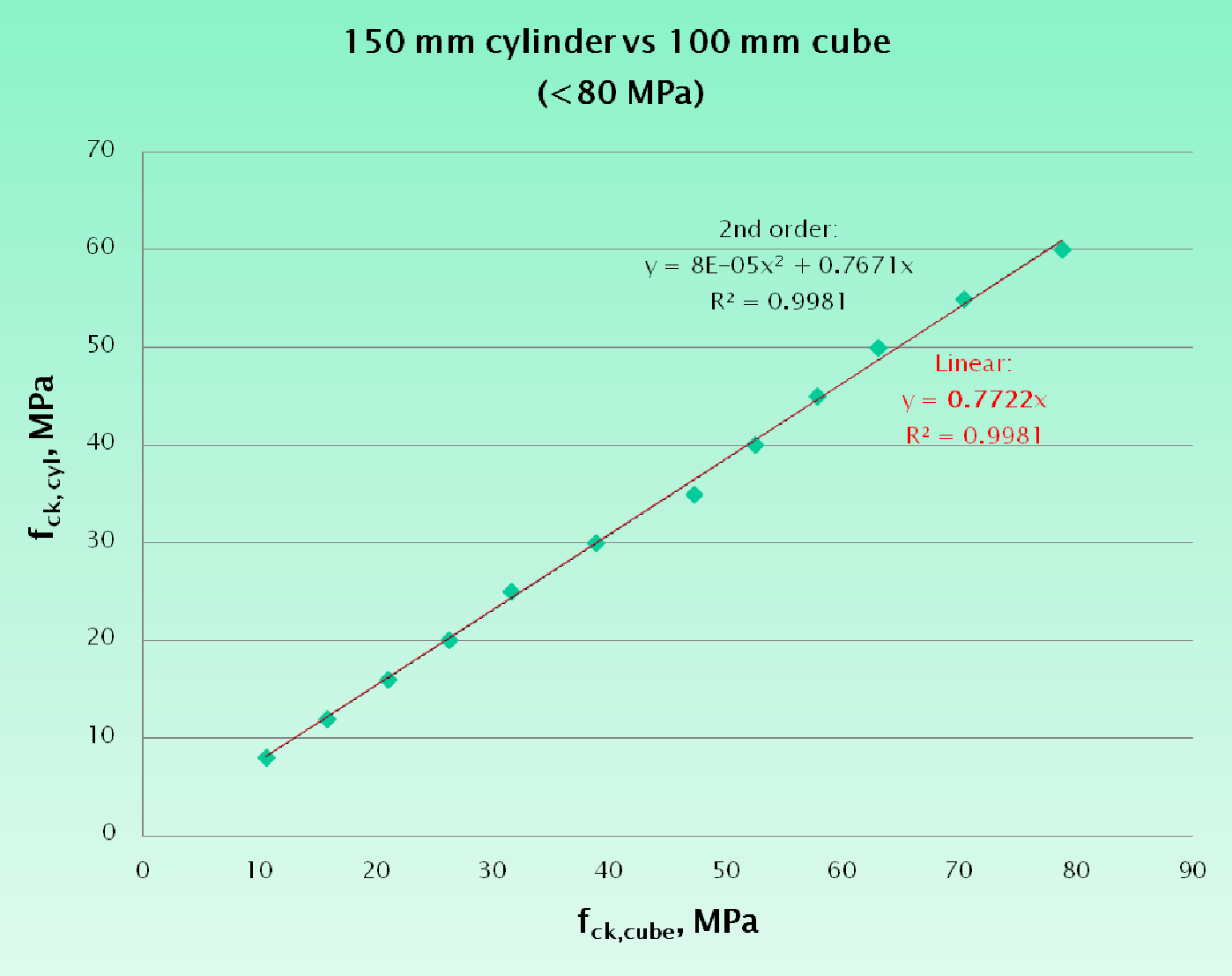
3. Analysis of test results by PWCL

Relationship between 150 mm dia. cylinders, 150 mm cubes and 100 mm cubes strength

Compressive strength class in BS EN 206-1	Characteristic Strength, MPa			Cylinder/100mm-cube ratio
	Cylinder $f_{ck,cyl}$	150mm-cube $f_{ck,150\,mm-cube}$	100mm-cube $f_{ck,100\,mm-cube}$	
C8/10	8	10	11	0.73
C12/15	12	15	16	0.75
C16/20	16	20	21	0.76
C20/25	20	25	27	0.74
C25/30	25	30	32	0.78
C30/37	30	37	39	0.77
C35/45	35	45	48	0.73
C40/50	40	50	53	0.75
C45/55	45	55	58	0.78
C50/60	50	60	63	0.79
C55/67	55	67	71	0.77
C60/75	60	75	79	0.76
C70/85	70	85	90	0.78
C80/95	80	95	100	0.80
C90/105	90	105	111	0.81
C100/115	100	115	121	0.83

3. Analysis of test results by PWCL

Best fitting curve from Table 7 of BS EN 206-1 modified for 100 mm cubes



4. Discussion

- Based on characteristic values, PWCL found an almost linear relationship of y=0.788x between 150 mm dia. cylinders (y) and 100 mm cubes (x) strength for concrete of grade 80 MPa or below.
- HKU proposed a linear relationship of y=0.78x for concrete grade 80 MPa or below.
- Based on BS EN 206 Table 7, a linear relationship of y=0.772x (modified for 100 mm cubes) is obtained for concrete of grade 80 MPa or below.
- From the above, it is noted that the difference between the cylinder/cube ratio in Eurocode and the results obtained from this study is only by a negligible margin of about 2%.
- However, the study is only based on 119 cylinders and 119 cubes. As the characteristic strength is affected by the standard deviation and this study is generally based on a set of 3 mean values obtained for each grade strength, PWCL proposed that the Eurocode relationship should be maintained for local concrete but modified for 100 mm cubes.

5. Conclusion

- The results of this study confirmed that the strength ratio (150 mm dia. cylinder vs. 100 mm cube) for local concrete is similar to that of Eurocode. The difference is about 2%.

- As this study is based on limited samples (119 cylinders and 119 cubes), it is proposed that the Eurocode relationship should be maintained for local concrete but modified for 100 mm cubes.

The contribution from the following parties for their support to the study is gratefully acknowledged:

- HKU
- CPA
- DSD
- WSD

End of presentation

Thank you!